

Medium Modifications of Charm and Charmonium in High-Energy Heavy-Ion Collisions

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Abstract. The production of charmonia in heavy-ion collisions is investigated within a kinetic theory framework simultaneously accounting for dissociation and regeneration processes in both quark-gluon plasma (QGP) and hadron-gas phases of the reaction. In-medium modifications of open-charm states (c -quarks, D -mesons) and the survival of J/ψ mesons in the QGP are included as inferred from lattice QCD. Pertinent consequences on equilibrium charmonium abundances are evaluated and found to be especially relevant to explain the measured centrality dependence of the ψ'/ψ ratio at SPS. Predictions for recent $In-In$ experiments, as well as comparisons to current $Au-Au$ data from RHIC, are provided.

1. Introduction

Heavy-flavor bound states constitute a valuable probe of the hot/dense strongly interacting matter formed in relativistic collisions of heavy nuclei. It was first suggested in [1] to identify J/ψ suppression as a signature of a deconfined medium due to color Debye screening, with tightly bound $c\bar{c}$ states presumably being robust in a hadron gas (HG). However, more recently it has been realized that c -quark reinteractions in the medium can lead to regeneration of charmonium states through c - \bar{c} coalescence [2, 3], especially if charm production is abundant (*e.g.*, $N_{c\bar{c}} \sim 10$ -20 in central $Au-Au$ collisions at RHIC).

Further insights into charm(onium) properties at finite temperature T have recently been provided by lattice QCD (LQCD) calculations which indicate (*i*) a continuous reduction of the open-charm threshold with increasing matter temperature [4] and (*ii*) the survival of low-lying charmonia ($\eta_c, J/\psi$) up to $\sim 2 T_c$ [5, 6, 7].

We here present an approach to charmonium production at SPS and RHIC [8] in which in-medium charm properties are modeled in accord with LQCD results and implemented into a kinetic rate equation, solved for a schematic thermal fireball expansion [9]. It enables a simultaneous treatment of charmonium dissociation and regeneration throughout the evolution of the system, thus improving on our earlier constructed “two-component” model [10, 11] where suppression in QGP and HG was combined with statistical production at hadronization.

2. In-medium properties of open and hidden charm in equilibrium

LQCD calculations at finite T show that the free energy of a static heavy-quark pair ($Q\bar{Q}$), $F_{Q\bar{Q}}=V-TS$, reaches a (constant) plateau at large spatial separation [4], which decreases with increasing T , continuously across the phase transition. We associate this behavior with a decreasing open-charm threshold[†]; in the hadronic phase, a plausible interpretation is provided by the (partial) restoration of chiral symmetry: as T increases, we expect a reduction of constituent light-quark masses, inducing smaller D -meson masses. The evaluation of the former, within a NJL model at finite temperature and density, typically amounts to $\Delta m(T_c) \simeq -140$ MeV. Requiring continuity across T_c , the effective charm-quark mass in the QGP is around $m_c^* \simeq 1.6$ -1.7 GeV, which might be associated with a thermal correlation energy of c -quarks.

At a fixed number, $N_{c\bar{c}}$, of $c\bar{c}$ pairs in the system (as expected for production exclusively in initial N - N collisions), in-medium modified open-charm states affect the (thermal) equilibrium abundance of charmonia Ψ , given by the densities $n_\Psi^{\text{eq}}(T, \gamma_c) = d_\Psi \gamma_c^2 \int \frac{d^3q}{(2\pi)^3} f^\Psi(m_\psi, T)$, where f^Ψ are Bose distribution functions (using vacuum Ψ masses), and d_Ψ is a spin-isospin degeneracy. The charm-quark fugacity γ_c encodes chemical off-equilibrium effects being adjusted to $N_{c\bar{c}}$ through

$$N_{c\bar{c}} = \frac{1}{2} \gamma_c N_{\text{op}} \frac{I_1(\gamma_c N_{\text{op}})}{I_0(\gamma_c N_{\text{op}})} + V \sum_{\Psi=\eta_c, J/\psi, \dots} n_\Psi^{\text{eq}}(T, \gamma_c), \quad (1)$$

where $N_{\text{op}} = V n_{\text{op}}(m_{c,D}^*; T)$ denotes the total equilibrium number of open-charm states in either QGP (c, \bar{c} quarks) or HG phase (charmed hadrons). In the QGP, an in-medium c -quark mass, larger than the perturbative value of $m_c \sim 1.2$ GeV, leads to an increase in Ψ equilibrium abundances since it becomes energetically favorable to distribute $c\bar{c}$ pairs into Ψ states, especially if $m_\Psi < 2m_c^*$. Conversely, in the hadronic phase, reduced in-medium D -meson masses lower the Ψ equilibrium level.

3. Rate equations in heavy-ion collisions

To make contact with the dynamical situation encountered in heavy-ion collisions, we employ a kinetic theory framework. If open-charm states are in thermal equilibrium, the evolution equation for the number, N_Ψ , of charmonium states present in the system is given by $\frac{dN_\Psi}{d\tau} = -\frac{1}{\tau_\Psi} [N_\Psi - N_\Psi^{\text{eq}}]$. The charmonium equilibrium numbers N_Ψ^{eq} are determined as described above, except, however, for additional thermal off-equilibrium corrections expected in heavy-ion collisions, namely: (i) a thermal relaxation time which effectively reduces N_Ψ^{eq} during the early times of the collision (see [11] for details), and (ii) a correlation volume V_{corr} implemented into the argument of the Bessel functions in Eq. (1) to account for the locality of $c\bar{c}$ production. The thermal widths of charmonia, $\Gamma_\Psi = (\tau_\Psi)^{-1}$, are obtained by convoluting their inelastic cross sections with thermal distributions of the matter constituents. In the QGP phase, we use parton-induced “quasifree” breakup reactions [10], $i + \Psi \rightarrow i + c + \bar{c}$ ($i = g, q, \bar{q}$), accounting for the different binding energies of the respective charmonium states (ψ, ψ' and χ). In the HG, we compute J/ψ breakup by pions and rhos within a flavor- $SU(4)$ effective lagrangian formalism (see [12] and references therein), augmented by geometric scaling for the ψ' and χ . Here, the consequences of in-medium D -meson masses are two-fold: first, inelastic reaction rates increase due to a larger

[†] Note that for a quantitative assessment, the entropy term in $F_{Q\bar{Q}}$ should be removed.

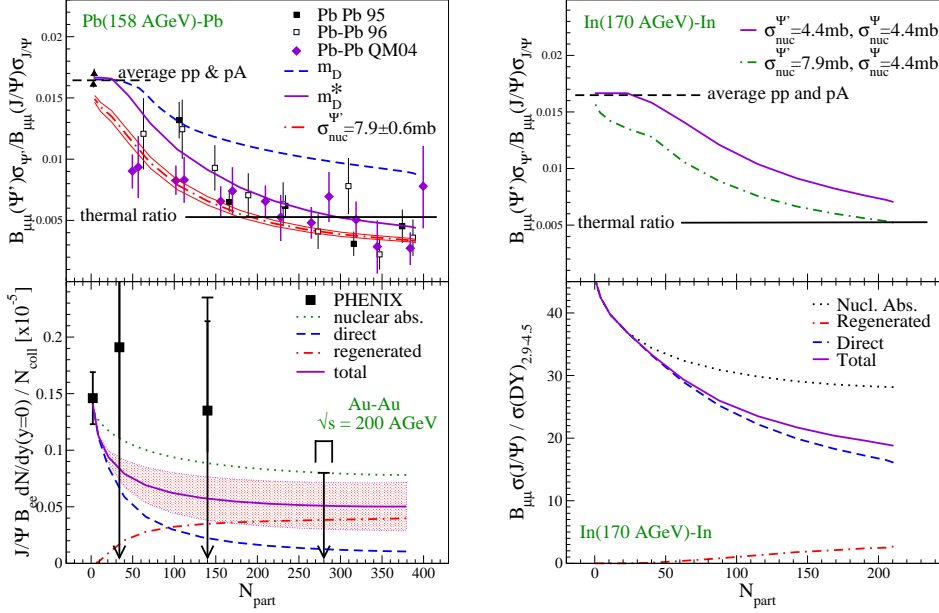


Figure 1. Upper left panel: ψ'/ψ ratio in $Pb(158 \text{ AGeV})\text{-}Pb$ at SPS; solid (dashed) line: with (without) in-medium effects using a uniform nuclear absorption cross section $\sigma_{nuc} = 4.4 \text{ mb}$; dash-dotted line: as solid line but with an updated value for the ψ' nuclear absorption cross section, $\sigma_{nuc}^{\psi'} = 7.9 \pm 0.6 \text{ mb}$. Lower left panel: $J/\psi/N_{coll}$ at mid-rapidity vs. N_{part} in 200 AGeV $Au\text{-}Au$ at RHIC. The total yield (full curve) is dominated by regenerated J/ψ 's (dash-dotted curve) with almost no direct J/ψ 's remaining (dashed curve). The band reflects the uncertainty on the magnitude of in-medium effects. Upper (lower) right panel: centrality dependence of the ψ'/ψ ($J/\psi/DY$) ratio in $In(170 \text{ AGeV})\text{-}In$ at SPS.

available phase space and second, the $D\bar{D}$ threshold can move below the charmonium mass, which additionally enables direct decays $\Psi \rightarrow D\bar{D}$ [13]. The rate equations are supplemented by initial conditions, N_{Ψ}^0 , for which we take experimental yields from pp extrapolated in centrality by $N\text{-}N$ collision scaling and “pre-equilibrium” nuclear absorption. The rate equations are then integrated over the space-time history of the collision according to a schematic thermal fireball evolution [9].

4. Comparison with experiments

Pb-Pb at SPS – At SPS energies ($\sqrt{s_{NN}}=17.3 \text{ GeV}$), primordial charmonium production is large compared to charmonium equilibrium abundances, $N_{\Psi}^0 \gg N_{\Psi}^{eq}$, implying little regeneration. As shown in [8], the centrality dependence of the J/ψ over Drell-Yan ratio in $Pb\text{-}Pb$ collisions is well reproduced and QGP formation is characterized by J/ψ suppression. The consequences of in-medium effects at SPS are particularly pronounced in the ψ'/ψ ratio, cf. the upper left panel of Fig. 1. With vacuum D -meson masses (dashed line) our calculation underestimates ψ' suppression. The calculation including medium effects (full line) improves the agreement with NA50 data [14] substantially, which is a direct consequence of the reduction of the $D\bar{D}$ threshold in the HG, opening the $\psi' \rightarrow D\bar{D}$ decay channel. The ψ' data set (including $p\text{-}A$ collisions) has recently been reanalyzed by NA50 [15] (diamonds), deducing a

stronger nuclear absorption of the ψ' , $\sigma_{\text{nuc}}(\psi') = 7.9 \pm 0.6 \text{ mb} > \sigma_{\text{nuc}}(\psi) = 4.4 \text{ mb}$. Our calculation with the correspondingly updated values of σ_{nuc} is shown by the dash-dotted line, confirming the need for in-medium effects to reproduce the ψ'/ψ ratio.

Predictions for In-In at SPS – The NA60 collaboration will continue to study charm(onium) production at SPS and we present in the right panel of Fig. 1 our predictions for the ψ'/ψ and $J/\psi/DY$ ratios as a function of centrality in $In(170 \text{ AGeV})$ - In collisions. Similar to the Pb - Pb system, J/ψ regeneration (dash-dotted curve in the lower right plot) is rather limited and the main effect remains J/ψ suppression (dashed curve) exhibiting a marked departure from nuclear absorption (dotted line). Medium effects are still appreciable, as illustrated in the upper right panel where a gradual decrease of the ψ'/ψ ratio is predicted as a function of N_{part} .

RHIC results – Our calculations at full RHIC energy ($\sqrt{s_{NN}} = 200 \text{ GeV}$) are compared to published PHENIX data [16] in the lower left of Fig. 1. Contrary to SPS, the J/ψ yield in central Au - Au collisions (full curve) is dominated by regenerated J/ψ 's (dash-dotted curve) while primordial J/ψ 's are almost completely suppressed (dashed line). The uncertainty linked to our treatment of in-medium effects is reflected by the band corresponding to $-250 < \Delta m_D(T_c) < -80 \text{ MeV}$, with stronger in-medium effects resulting in a smaller J/ψ yield.

5. Conclusions

We have presented a model for charmonium production in heavy-ion collisions incorporating in-medium effects on open-charm states, as inferred from Lattice QCD, within a kinetic rate equation which allows to comprehensively treat suppression and regeneration mechanisms during the course of the collision. We have found that QGP formation manifests itself by J/ψ suppression at SPS energies and by J/ψ regeneration at RHIC, where run-4 data are expected to give important insights. In-medium effects have so far proved to be essential to understand the centrality dependence of the ψ'/ψ ratio at SPS. Our predictions can also be tested by upcoming NA60 data for In - In collisions at SPS. Complementary studies of charmonium transverse momentum distributions, as well as charmonium and bottomonium production at LHC, will provide further scrutiny of the proposed approach.

References

- [1] Matsui T and Satz H 1986 *Phys. Lett. B* **178** 416
- [2] Braun-Munzinger P and Stachel J 2000 *Phys. Lett. B* **490** 196 *Preprint* nucl-th/0007059
- [3] Thews R L, Schroedter M and Rafelski J 2001 *Phys. Rev. C* **63** 054905 *Preprint* hep-ph/0007323
- [4] Karsch F, Laermann E and Peikert A 2001 *Nucl. Phys. B* **605** 579 *Preprint* hep-lat/0012023
- [5] Datta S, Karsch F, Petreczky P and Wetzorke I 2002 *Preprint* hep-lat/0208012
- [6] Umeda T, Nomura K and Matsufuru H 2002 *Preprint* hep-lat/0211003
- [7] Asakawa M and Hatsuda T 2004 *Phys. Rev. Lett.* **92** 012001 *Preprint* hep-lat/0308034
- [8] Grandchamp L, Rapp R and Brown G E 2003 *Preprint* hep-ph/0306077
- [9] Rapp R and Wambach J 2000 *Adv. Nucl. Phys.* **25** 1 *Preprint* hep-ph/9909229
- [10] Grandchamp L and Rapp R 2001 *Phys. Lett. B* **523** 60 *Preprint* hep-ph/0103124
- [11] Grandchamp L and Rapp R 2002 *Nucl. Phys. A* **709** 415 *Preprint* hep-ph/0205305
- [12] Duraes F O, Kim H C, Lee S H, Navarra F S and Nielsen M 2002 *Preprint* nucl-th/0211092
- [13] Friman B, Lee S H and Song T 2002 *Phys. Lett. B* **548** 153 *Preprint* nucl-th/0207006
- [14] Abreu M C *et al* (NA50 Collaboration) 1998 *Nucl. Phys. A* **638** 261
- [15] Santos H (NA50 Collaboration) 2004 these proceedings
- [16] Adler S S *et al* (PHENIX Collaboration) 2003 *Preprint* nucl-ex/0305030